Wind profiles in and over trees

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Abstract: One of the most important and frequently studied variable in forests and the most basic element in governing transport processes of airflow is wind speed. The study of wind profile, defined as the change of wind velocity with height, and wind velocity are important because of tree physiological and developmental responses. Generally, wind profiles above the ground or at a canopy surface follow classical logarithm law, but wind profiles in a single tree and in a forest stand are not logarithmic. This paper summarizes the results of wind profile studies within a single tree, in a forest stand, above the forest canopy and in a forest area from recent research in a coastal pine forest. The results demonstrate that: 1) wind profiles with in a single conifer tree crown showed an exponential function with height, 2) wind profiles in forest stands were able to be expressed by attenuation coefficient of wind, 3) wind profiles over a forest canopy could be determined using profile parameters (friction velocity, roughness length and displacement), and 4) for a forest area, the extreme wind speed could be predicted reasonably using the methods developed for the design of buildings. More research will be required to demonstrate: 1) relationships between wind profiles and tree or stand characteristics, 2) the simple methods for predicting wind profile parameters, and 3) the applications of wind profile in studies of tree physiology, forest ecology and management, and the detail ecological effects of wind on tree growth.

Key words: Wind; Wind profile; Trees; Forest ecology

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Introduction

One of the most important and most frequently studied variables in forests and those most basic in governing transport processes and dispersion of airflow are wind speed and temperature (Raynor 1971; Zhu *et al.* 2000). Wind causes extensive forest damage and large amounts of soil being wind eroded and transported to another location, and it is also a major factor influencing other microclimate factors such as the heat and vapor exchange near the soil surface (Coutts and Grace 1995; Peltola *et al.* 2000), the transfer processes of insects and disease, and the growth of trees (Hannah *et al.* 1995). In all of these interactions, the wind profile, i.e., the change of wind velocity with height, is very important, because both physiological and developmental responses of trees to wind are sensitive to the shape of the wind magnitude and height. Therefore, much research has been carried out to understand the physical processes involved so as to enhance silvicultural practices and forest management (Landsberg and James 1971; Oliver 1971; Kotoda and Hayashi 1980; Cionco 1985; Ishizaki and Ota 1987; Gardiner 1995; Liu & Kotoda 1996; Lemone *et al.* 1998; Zhu *et al.* 2004).

The variation of wind speeds with height from a surface can be expressed empirically by various formulae. Generally, for ground level studies and for moderate or strong winds, the wind profile expressed by equation (1) is valid (Raynor 1971; Oliver and Mayhead 1974; Lyles and Allison 1979; Kimmins 1987; Abtew *et al.* 1989; Dyrbye and Hansen 1997; Maki 1999; Zhu *et al.* 2001a).

$$U_z = u_* \frac{1}{\kappa} \ln(\frac{z-d_0}{z_0}) + \Phi_z \tag{1}$$

where U_z is the horizontal mean wind velocity ($m \cdot s^{-1}$) at height z, u_* is the friction velocity ($m \cdot s^{-1}$), κ is von Karman's constant (0.40, dimensionless); z is the height of measurement from a reference plane (m); d_0 is the zero-plane displacement (m); z_0 is the roughness parameter (m); and Φ_z indicates that mean velocity also depends on Richardson's number (R_i, dimensionless).

The wind profile (equation 1) has been applied in many studies. When we consider the motion of air in a tree or a forest stand, it becomes quite apparent that airflow within the tree crown and forest canopy is a significant aspect of the surface boundary layer (Cionco 1985).

The aerodynamic characteristics of forest stand have been an interest to forestry and agriculture for a long time, particularly in regard to the classic problems such as wind

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damage, seed transport, disease and insect control, and fire prevention. More complex approaches to explore the atmospheric constituents that are affected by airflow interacting with vegetative structures have also been carried out. Several meteorological models have been constructed and much data collected (Reifsnyder 1955; Taketa 1965; Allen 1968; Raynor 1971; Kotoda and Hayashi 1980; Amiro 1990a, b; Lemone *et al.* 1998). It has thus been shown that the wind profile is the most sensitive indicator of the degree and effectiveness of turbulence (Bull and Reynolds 1968; Gardiner 1995). Additionally, wind profile is also important in assessing wind damage or stand stability (Blackburn and Petty 1988b; Peltola 1996b; Gardiner *et al.* 1997), and in examining wind effects on microclimates in forest stand, e.g., on the distribution of rainfall, light and some gases (Telewski 1995; Kuraji *et al.* 1997). The objective of this paper is to summarize the research results from wind within a single tree to wind over a forest stand based on the studies of wind and management of a coastal pine forest in Niigata, Japan.

Wind speed within a single tree crown

Prediction of wind speed in a single tree crown as a function of position within the crown, crown structure and external wind is important for solving the problems of tree or stand damage by wind. The movement of air at all levels of a crown is important in the study of transfer processes among leaves, branches and their immediate environment (Murai *et al.* 1992; Zhu *et al.* 2000). Zhu *et al.* (2000) established a model of airflow within a single tree crown, with studies of Japanese black pine (*Pinus thunbergii* Parl.). Two Japanese black pine trees were examined and wind speeds at three vertical sections: $VS_{(NS)}$, oblique to wind direction; $VS_{(P1)}$, perpendicular to wind direction and; $VS_{(PA)}$, along or parallel to wind direction) of the trees were measured.

In a conifer tree crown, the exponential form given in equation (2) is appropriate to describe the vertical wind profile (Zhu *et al.* 2000).

$$U_{in(z)} = U_{out(z)} \exp[-\alpha_s (1 - \frac{z}{H})] \qquad (2)$$

where $U_{in(z)}$, $U_{out(z)}$ are wind speeds within and without a tree crown at height z ($m \cdot s^{-1}$), respectively, *z* is the interest height in the crown (m), H is the height of the tree crown (m), α_s is a constant (dimensionless).

Regressions were made to estimate the parameter α_s by the wind speed data observed from the vertical sections of trees (Zhu *et al.* 2000). For estimating α_s accurately, it is desirable to measure more individual vertical sections. However, it should be noted that accurate measurement of $U_{in(z)}$ is always likely to be difficult in practice, because an instrument mounted in a tree crown is subject to the effect of local variability in the tree crown. The presented results indicated no significant difference among the vertical wind profiles, which were obtained from the total average, center average and the 3 vertical sections, respectively (p <0.05). Therefore, the wind measurement only at the center range (0.5 m around the stem) can provide the value of α_s accurately for an individual tree. The measurement should be arranged in perpendicular to, or along with the wind direction (Zhu *et al.* 2000).

Therefore, wind speed within a single tree crown at height *z* ($U_{in(z)}$) was estimated from the vertical wind profile by giving a constant value of α_s, together with a measurement of $U_{out(z)}$. However, the wind speed $U_{in(z)}$ estimated from the vertical wind profile should only represent the mean wind speed at height *z* of the trunk, leastwise the center theoretically. It is necessary in some cases to estimate the wind speed at other positions within the crown but not at the trunk. For this reason, a horizontal wind profile expressed using crown thickness (CT) is developed (equation 3). CT as an indicator of tree crown characteristics, was defined as a horizontal distance from the points for wind speed measurement in the observed section to the outer edge of a crown in windward direction, which was measured corresponding to the points of wind speed observations at each height.

$$U_{in(z)} / U_{out(z)} = \varepsilon_0 \exp(\varepsilon CT) \qquad (3)$$

where ε is a parameter to determine wind speed within a single tree crown according to crown thickness (dimensionless); ε_0 is a constant, given based on the mean values of relative wind speed from the observation of the three vertical sections (dimensionless), it is different according to various heights (Lower, Middle and Upper) (Fig. 1).

Trees with longer crown thickness indicated a more wind reduction within the crown. The differential ratio $dU_{(inz)}/dCT$ can be described from an empirical regression expressed as in equation (3). Therefore, the wind speed at a horizontal plane within the crown can be estimated by providing parameter ε and CT.

The vertical and horizontal wind profiles within a single tree crown of Japanese black pine can be orderly described in terms of height *z* and crown thickness as exponential functions, respectively. If the assumption that the estimated wind speed within the crown from vertical wind profile representing the mean wind speed at height *z* of the trunk is reasonable, then parameter ε in equation (3) can be derived from a single crown thickness measurement at the height corresponding to the estimated wind speed ($U_{in(z)}$). This is because the wind direction can be observed from instrument, and the crown thickness corresponding to the height *z* (distance from the trunk to the outer edge of the crown along the wind direction) can be measured. Using the equation (3) with known parameter ε, wind speed at any position within the crown at a certain height (Lower, Middle or Upper) can be estimated reasonably.

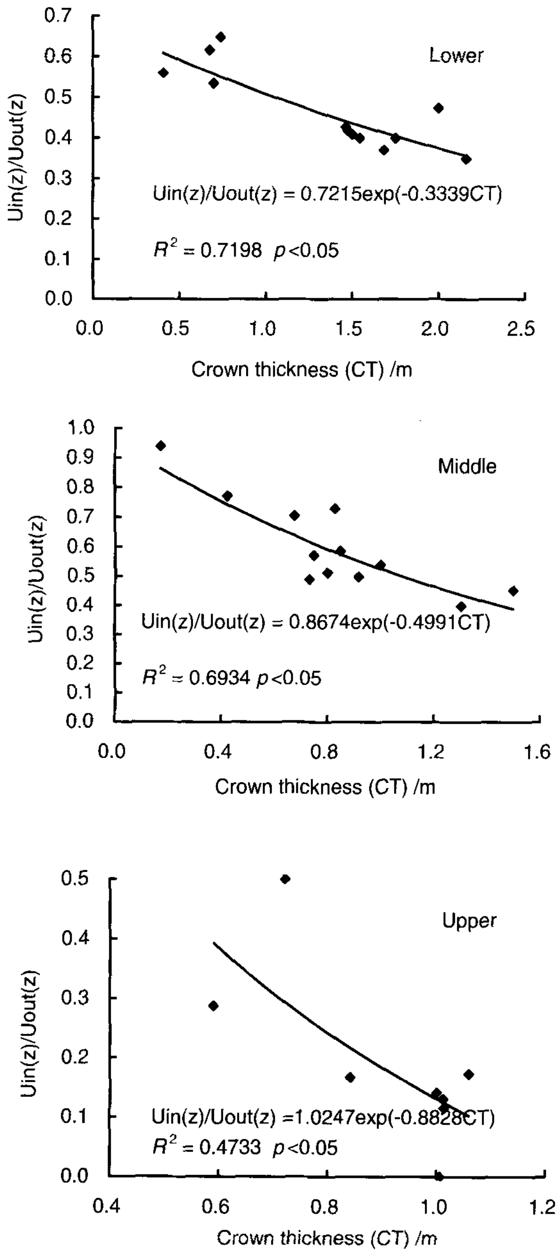

Fig. 1 Relationship between crown thickness (CT) and relative wind speed for total average from the three observed sections (Three parts, Lower, Middle and Upper were divided).

Wind profiles inside the forest stand

The analytical model for air movement within plant canopies developed in the literatures (Plate 1971; Bergen 1971; Landsberg and James 1971; Kondo and Akashi 1976; Cionco 1985) equates the canopy to a two-dimensional distribution of infinitesimal momentum sinks corresponding to the canopy surfaces (Bergen 1971). The average flow in a horizontal plane is determined by a balance between the average divergence of shearing stress at that level and the drag per unit volume exerted by the canopy surfaces. The modeling of airflow within plant canopies described by Landsberg and James (1971), Thom (1971), Kondo and Akashi (1976), Cionco (1985) and Amiro (1990a) as

$$\frac{\partial \tau_0}{\partial z} = D_0 U_{in(z)}^{\ 2} \ (z<H) \tag{4}$$

where $U_{in(z)}$ is wind speed within canopies ($m \cdot s^{-1}$), H is height of canopy top and the nominal tree height (m), and D_0 is the drag-vegetative attenuation factor defined as

$$D_0 = \frac{1}{2}\rho C_d A_{(z)} \tag{5}$$

where C_d is drag coefficient (non-dimension), $A_{(z)}$ is the derivative of the leaf index with height (non-dimension).

The model of airflow within canopies was formulated as exponential function of height in equation (6).

$$U_{in(z)} = U_H \exp[-\alpha(1-\frac{z}{H})] \tag{6}$$

where U_H is wind speed ($m \cdot s^{-1}$) at height of canopy top H; α is a constant coefficient related to momentum absorption (non-dimension). The canopy flow index (attenuation coefficient) α determines the form of wind profile within canopy, and defined as equation (7) by Landsberg and James (1971); as equation (8) by Kondo and Akashi (1976) and Cionco (1985).

$$\alpha = H\sqrt{\frac{C_d U_H L}{6K_m}} \tag{7}$$

where L is the average foliage density related to the leaf index.

$$\alpha = h\sqrt{\frac{D_0}{2L_{c0}^2}} \tag{8}$$

where L_{c0} is mixing length within the canopy (m).

Studies show that for the wind profiles in the trunk layer, at least on some occasions, bulge (Oliver 1975) or secondary wind speed maximum (Gardiner 1994) is found in the trunk layer (Oliver 1975; Zhu *et al.* 1998). This finding has sometimes been explained by some blow-through phenomenon (Landsberg and James 1971) associated with edge effects, large gaps of forest or non-horizontal site and so on.

In this study, wind profiles within the canopies of thinned and unthinned coastal pine stands were plotted according to various wind directions (Fig. 2).

Obviously, the influence of wind direction on wind profile was stronger in the trunk layer than within the canopy layer. In the trunk layer, greater changes of wind direction, ranging from 46 to 180 degrees true north, were found for both thinned and unthinned stands. There was evidence that a certain amount of secondary maximum wind speed existed

in almost all of wind directions for the thinned stand, namely, wind velocity actually increased below the height under canopy and caused a negative gradient ($du/dz<0$). However, there was no obvious secondary maximum occurring in the trunk layer of the unthinned stand. The phenomenon may be attributed to the fact that there was vacant space in the canopy of the thinned stand through which pressure pulses or gust of airflow could permeate to the bottom and spread from there.

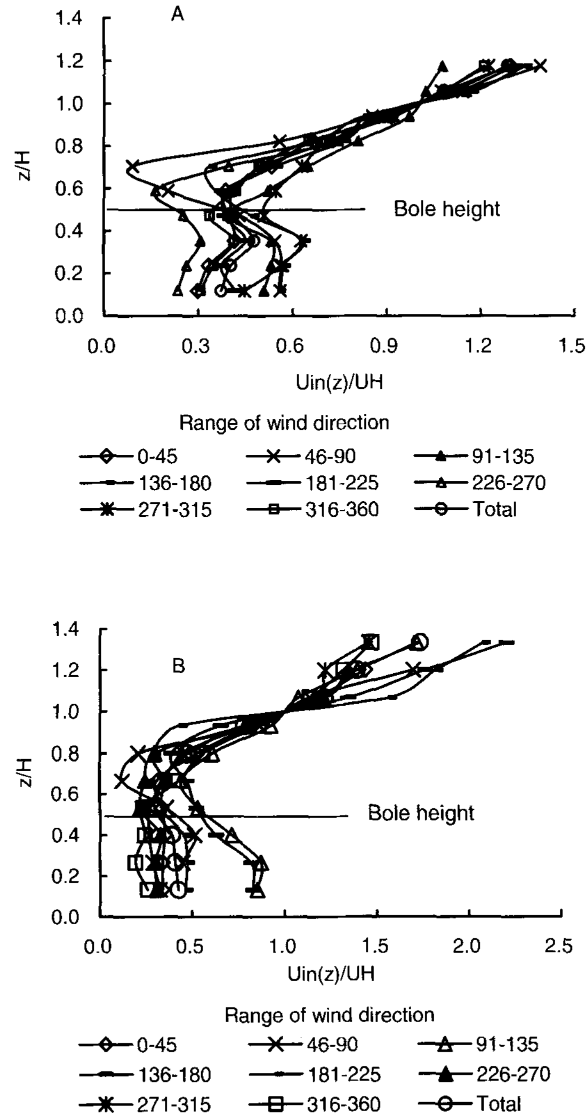

Fig. 2 Wind profiles plotted according to wind direction for coastal pine thinned (A) and unthinned (B) stands.

In the crown layer, the difference between the thinned and unthinned stands in wind profiles influenced by wind direction could be compared quantitatively using the attenuation coefficient α (equation 6). The parameter α was smaller for the winds with the windward direction (ranging from 271 to 45 degree true north) than those for the winds with other directions, and it was unstable for the winds with a leeward direction. The mean value of the attenuation coefficient α was determined as 2.2 and 3.4 for thinned and unthinned stands, respectively. This means that the foliage density in unthinned stand is larger than that of thinned stand (Peltola 1996b). In the trunk layer, the wind profiles can not be expressed using equation (6) because of the negative gradient of wind speed.

Wind profiles above the canopy

The earlier numerical models used concepts of eddy diffusivity, mixing length (L_0) and the shearing stress (τ_0) to describe the wind profiles above the canopy (Taketa 1964; Thom 1971, 1972; Kondo and Akashi 1976; Cao 1983; Cionco 1985; Kaimal and Finnigan 1994; Asai 1996; Liu and Kotoda 1996), i.e., logarithm law of velocity. For an idealized uniform forest expanse, the wind regime is generally assumed to have a uniform flow with a constant vertical shearing stress above the canopy in adiabatic conditions (Munn 1966; Bergen 1971). The shearing stress of momentum flux can be expressed as

$$\tau_0 = K_m \rho \frac{\partial U}{\partial z} \tag{9}$$

where K_m is the exchange coefficient of momentum ($m^2 \cdot s^{-1}$), ρ is air density ($kg \cdot m^{-3}$), U is the wind velocity ($m \cdot s^{-1}$), z is height (m).

$$K_m = L_0 u_* \tag{10}$$

where L_0 is mixing length (m), u_* is friction velocity ($m \cdot s^{-1}$). They are defined as

$$L_0 = \kappa z \tag{11}$$

where κ is von Karman's constant (≈ 0.40), and

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \tag{12}$$

Substituting the above expressions for K_m in equation (10) gives,

$$\frac{\partial U}{\partial z} = \frac{u_*}{\kappa z} \tag{13}$$

The above mentioned assumptions imply that the shearing stress is constant above the canopy or a surface layer, and z is the only length scale determining the shearing stress. Integrating equation (13) gives the classical logarithm law of velocity of the constant-flux (equation 14, the same as equation 1).

$$U_z = \frac{u_*}{\kappa}[\ln(\frac{z-d_0}{z_0})] \tag{14}$$

The parameters u_*, d_0 and z_0 in the equation of logarithm velocity law are called as wind profile parameters. Of which, d_0 and z_0 can be calculated from equation (14) as

$$d_0 = z - z_0 \exp(\frac{U_z}{\kappa u_*}) \tag{15}$$

$$z_0 = \frac{z - d_0}{\exp(\frac{U_z}{\kappa u_*})} \tag{16}$$

Strictly, equation (14) is just fitted for neutral condition (Aloysius 1995). When it is used in other conditions, it must be modified to conditions with non-neutral stability as equation (1).

Generally, for obtaining the reliable estimation of the parameters of d_0 and z_0 from the logarithm velocity law, it is necessary to make the measurement at least above height of 30 z_0. This is because the turbulent flow in the logarithm velocity law can be expressed as

$$\frac{U_z}{u_*} = \frac{1}{\kappa}\ln(\frac{z}{k_s}) + B \tag{17}$$

where k_s is the equivalent roughness parameter (m), z is height (m), B is a constant.

The logarithm velocity law can be applied only above the height of k_s. Coefficient B in equation (17) was determined as 8.48 in a situation of turbulent airflow (Xie 1987). Therefore, the effective height of k_s above the canopy of the forest can determined according to equations (14) and (17) as

$$k_s = \exp(B\kappa z_0) = 30 z_0 \tag{18}$$

The determination of parameter u_* was measured actually with the sonic anemometers. Here u_* is expressed as

$$u_* = \sqrt{-\overline{u'w'}} \tag{19}$$

where u' is longitudinal velocity fluctuation ($m \cdot s^{-1}$), and w' is vertical velocity fluctuation ($m \cdot s^{-1}$).

An order-of-magnitude of stability length (L'), calculated from the sonic anemometer measurements, showed a neutral condition for the observation. Therefore, d_0 and z_0 in the equation of logarithm velocity law for the coastal pine forest were estimated from equations (15) and (16) using the friction velocity u_*, respectively. A total of sixty 10-minute average profiles were used to calculate the parameters of d_0 and z_0. The estimated values for thinned and unthinned stands were listed in Table 1. There was considerable variation in the estimation of both displacement height (d_0) and roughness length (z_0). The displacement height d_0 varied between 7.7 m and 0.6 m for the thinned stand, and between 8.9 m and 1.3 m for the unthinned stand. The roughness length z_0 varied between 2.39 m and 0.18 m for thinned stand, and between 2.06 m and 0.06 m for unthinned stand. This result illustrated that estimating the parameters of d_0 and z_0 from wind speed profiles just above the canopy of the coastal pine forest was difficult, especially with the limited observations. The most reliable estimates of d_0 and z_0 in this experiment probably came from those observations during July 17 to July 31 of 1999 when the airflow blew perpendicular to the coastal pine forest. The average values of d_0 and z_0 were 5.74 m, 0.52 m and 5.56 m, 0.23 m for thinned and unthinned stands, which gave the values of d_0/H=0.72 and 0.79, z_0/H=0.06 and 0.03 for each of the stand, respectively. The mean values of d_0/H and z_0/H are similar to those obtained by other researchers (Landberg and James 1971; Gardiner 1994).

Table 1. Wind profile parameters above the canopy of thinned and unthinned stands.

Period	Thinned stand			Unthinned stand		
	u_*	d_0	z_0	u_*	d_0	z_0
Observed during July 17 to July 31 of 1999						
Maximum	0.57	7.73	1.08	0.61	8.88	0.61
Minimum	0.25	3.48	0.18	0.18	1.30	0.06
Mean	0.42	5.74	0.52	0.35	5.56	0.23
Observed during November 1 to December 27 of 1999						
Maximum	0.45	7.00	2.39	0.44	8.19	2.06
Minimum	0.37	0.64	0.26	0.32	4.02	0.15
Mean	0.39	3.17	1.26	0.39	6.63	0.67
Total Mean	0.41	4.46	0.89	0.37	6.09	0.45

Wind speed at a forest area

The determination of wind regime in a potential or existing forest area is an important aspect of any site assessment. For predicting annual wind speed for a forest area, Hannah *et al.* (1995) made an attempt to relate wind speed to topographic and geographic characteristics of the site in order to avoid the necessity for long-term on-site wind measurements. They concluded that the major variables relating to wind speed were altitude, 'topex' (a measure of the exposure of a site), roughness length and the distance from the coast.

Over a period of several decades, the extreme wind speeds can be analyzed using extreme value statistical methods such as Gumbel (type Ⅰ extreme value), Fréchet (type Ⅱ extreme value) and reverse Weibull (type Ⅲ extreme largest values) distributions (Gross *et al.* 1994; Simiu and Heckert 1996; Galambos and Macri 1999). The probability of occurrence of any value of hourly-mean wind speed can be described by a Weibull distribution fitted to the entire record of hourly values (Milne 1992; Quine 2000; Zhu *et al.* 2001b).

Wind data (sample interval was 5 s, 10-minute mean wind speed, wind direction, maximum wind speed and the corresponding direction) were collected above the coastal pine forest during the period from November 16 of 1998 to July 16 of 2000 without break (87 696 sets of wind data). The frequency of occurrence of 10-minute mean wind speeds greater than 2.0 $m \cdot s^{-1}$ was examined using

two-parameter Weibull function (equation 20) with the 10-minute wind data (Fig. 3).

$$P_w = \frac{b}{c}\left(\frac{V}{c}\right)^{b-1}\exp\left[-\left(\frac{V}{c}\right)^b\right] \tag{20}$$

where P_w is the probability of occurrence of wind speed greater than mean wind speed U ($m \cdot s^{-1}$), an exponent b (dimensionless) and a constant c ($m \cdot s^{-1}$) are parameters of Weibull distribution. The parameters b and c can be used to derive the parameters (mode and dispersion) of extreme value distribution (Simiu and Filliben 1980, 1982; Simiu *et al.* 1985).

The fitting data were limited to the wind speed greater than 5 $m \cdot s^{-1}$ to minimize the effect of the poorer accuracy of the 10-minute means at low wind speeds. The distribution was fitted to have b=1.36 and c=2.56 $m \cdot s^{-1}$.

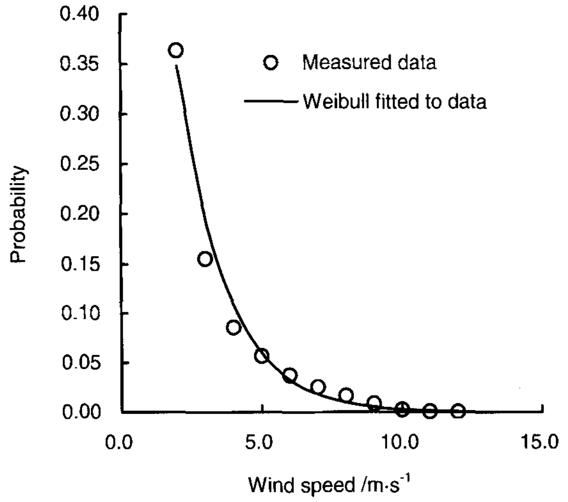

Fig. 3 Probability of occurrence for different 10-minute mean wind speeds over a coastal pine forest. The measured data and the Weibull distribution fitted to these measurements are compared.

Generally, a data set conforming to the Weibull distribution will have a cumulative distribution of its annual extreme values (Galambos and Marcri 1999; Quine 2000; Zhu *et al.* 2001b). The distribution of extreme values, which is usually used for building design purpose, is described by a Fisher-Tippett Type I distribution of the form in equation (21) (Miller 1982; Grigoriu 1984; Cheng and Chiu 1985; Gusella 1991; Milne 1992; Galambos and Marcri 1999; Quine 2000).

$$P_G(x) = \exp[-\exp(-y)] \tag{21}$$

where y is a reduced variate given as

$$y = \frac{1}{\lambda}(x - U_G) \tag{22}$$

$P_G(x)$ is the probability that an extreme value will be less than value x in any one year, U_G is the mode of the distribution (i.e., the most likely value of x) and $1/\lambda$ is the dispersion, i.e., a measure of the width of the distribution of x (Milne 1992; Simiu and Heckert 1996; Quine 2000).

The extreme wind speed, U_{extr} corresponding to a recurrence interval or return period, T_{extr} (in years) is given as

$$T_{extr} = \frac{1}{1 - P_G(x)} \tag{23}$$

In equation (22), it has been found that equating x to the square of wind speed (U_{extr}^2) rather than wind speed (U_{extr}) gives a better fit to the wind speed maximum (Milne 1992; Quine 2000). Thus, integrate equations (21)–(23), the extreme wind speed (U_{extr}) corresponding to an observation period of T_{extr} years can be calculated from equation (24).

$$U_{extr}^2 = U_G - \frac{1}{\lambda}\ln\left[-\ln\left(1 - \frac{1}{T_{extr}}\right)\right] \tag{24}$$

where the parameters U_G and λ can be estimated according to the method using Weibull parameters b and c, which is suggested by Milne (1992), that is, $(U_G)^{1/2}/c$ is a simple function of b, and λU_G is approximately constant for an area. Therefore, the function of $(U_G)^{1/2}/c$ is derived by a third order polynomial of b (equation 25) as suggested by Quine (2000), and $\lambda U_G \approx 5.0$.

$$\frac{\sqrt{U_G}}{c} = -0.5903b^3 + 4.4345b^2 - 11.8633b + 13.5690 \tag{25}$$

Generally, over a period of *m* days, data were collected for the highest wind speeds, while these observations are not independent. A method is suggested by Simiu and Heckert (1996) and examined by Galambos and Marcri (1999) for modifying the data to achieve stochastic independence. According to Simiu and Heckert's method, the relationships between the Gumbel distribution parameters (U_G and λ) and the expected value E(u), and standard deviation σ can be expressed as

$$\sqrt{U_G} = E(u) - 0.57722\left(\frac{\sqrt{6}}{\pi}\right)\sigma \tag{26}$$

$$\lambda = \left(\frac{\sqrt{6}}{\pi}\right)\sigma \tag{27}$$

The parameters of the Gumbel distribution were estimated in this way. Applying this function to the recorded data over the coastal forest provided an estimate of $U_G^{1/2}$= 11.8 ($m \cdot s^{-1}$) and $1/\lambda$= 27.7. From equation (24), the extreme 10-minute mean wind speed at the measurement height for a 50-year return period was calculated to be 15.7 $m \cdot s^{-1}$. The result showed that the approximation involved in both methods was in reasonable agreement. The probability that the extreme will be up to 25.0 $m \cdot s^{-1}$ in any one year period

was calculated from equation (21), and presented in Fig. 4. This result suggested that it was a reasonable estimate for the coastal forest area to use the method for engineering.

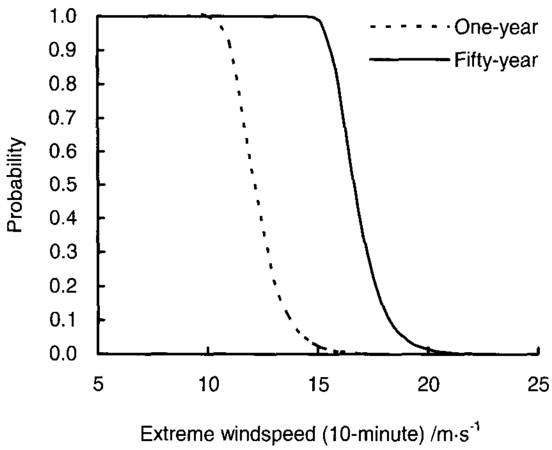

Fig. 4 Probability of extreme 10-minute mean wind speed over the coastal pine forest, being in the range from 5 m s^{-1} to 25 m s^{-1} for one-year and fifty-year periods.

Summary

Generally, wind profiles can be divided into two or three parts for a forest stand, i.e., within canopy (crown layer and trunk layer) and above canopy. There are many studies related to wind profiles within and above the various types of forest vegetations. This paper summarized the generalization of wind profiles in a coastal pine forest area. First, wind profile within a single tree crown was modeled through observations of wind speed within the single tree crown of Japanese black pine, and the wind speed within any position of the single tree crown could be estimated by a constant, crown thickness and wind speed outside the single tree crown. Second, wind profiles inside the coastal pine forest stands were established by exponential function with the attenuation coefficient. Meanwhile, the difference of wind profiles inside thinned and unthinned stands was expressed using the attenuation coefficient as well. Third, wind profile parameters (friction velocity, roughness length and displacement) over the coastal pine forest canopy were determined according to the ultrasonic observation. At last, the extreme wind speed at the coastal pine forest area was estimated with the methods developed for building design purposes. By summarizing the wind profiles in and over the forest stands, we found that some aspects such as relationships between wind profiles and the tree or stand characteristics, the simple methods for predicting wind profile parameters, and the applications of wind profile in studies of tree physiology, forest ecology and management, and the detail ecological effects of wind on tree growth should be studied further. Because wind has a very wide variety of ecological effects, and has played a very important role in the development of forestry.

References

Abtew, W., Gregory, J.M. and Borrelli, J. 1989. Wind profile: Estimation of displacement height and aerodynamic roughness [J]. Transactions of the ASAE, **32**: 521–527.

Allen, L.H. 1968. Turbulence and windspeed spectra within a Japanese larch plantation [J]. Journal of Applied Meteorology, **7**: 73–78.

Aloysius, K. 1995. Determination of zero-plane displacement and roughness length of a forest crown using profiles of limited height [J]. Boundary-Layer Meteorology, **75**: 381–402.

Amiro, B.D. 1990a. Comparison of turbulence statistics within three boreal forest canopies [J]. Boundary-Layer Meteorology, **51**: 99–121.

Amiro, B.D. 1990b. Drag coefficients and turbulence spectra within three boreal forest canopies [J]. Boundary-Layer Meteorology, **52**: 227-246.

Asai, T. 1996. Local meteorology [M]. University of Tokyo Press, Tokyo, 233 pp. (In Japanese)

Bergen, J.D. 1971. Vertical profiles of windspeed in a pine stand [J]. Forest Science, **17**: 314–321.

Blackburn, P. and Petty, J.A. 1988b. Theoretical calculations of the influence of spacing on stand stability [J]. Forestry, **61**: 235–244.

Bull, G.A.D. and Reynolds, E.R.C. 1968. Wind turbulence generated by vegetation and its application [J]. Forestry Supplement, 28–37.

Cao, Xinsun. 1983. Shelterbelt for Farmland [M]. Chinese Forestry Press, Beijing, 645 pp. (in Chinese)

Cheng, E.D.H. and Chiu, A.N.L. 1985. Extreme winds simulated from short-period records [J]. Journal of Structural Engineering, **111**: 77–94.

Cionco, R.M. 1985. Modeling windfields and surface wind profiles over complex terrain and within vegetation canopies [C]. In: Hutchison, B. A. and Hicks, B. B. (eds.), The forest-atmosphere interaction. D. Reidel publishing company, Dordrecht, Boston, Lancaster, pp 501–520.

Coutts, M.P. and Grace, J. 1995. Preface [C]. In: Coutts and M. P., Grace, J. (eds.), Wind and trees. Cambridge University Press, Cambridge, pp 9–10.

Dyrbye, C. and Hansen, S.O. 1997. Wind Loads on Structures [M]. Chichester, England: John Wiley and Son Ltd., 229 pp.

Galambos, J. and Macri, N. 1999. Classical extreme value model and prediction of extreme winds [J]. Journal of Structural Engineering, **125**: 792–794.

Gardiner, B.A. 1994. Wind and wind force in a plantation spruce forest [J]. Boundary-Layer Meteorology, **67**: 161–186.

Gardiner, B.A. 1995. The interaction of wind and tree movement in forest canopies [C]. In: Coutts, M. P. and Grace, J. (eds.), Wind and trees. Cambridge: Cambridge University Press, pp 41–59.

Gardiner, B.A., Stacy G.R., Belcher, R.E. and Wood, C.J. 1997. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability [J]. Forestry, **70**: 233–252.

Grigoriu, M. 1984. Estimates of extreme winds from short records [J]. Journal of Structural Engineering, **110**: 1467–1484.

Gross, J., Heckert, A., Slcchner, J. and Simiu, E. 1994. Novel extreme value estimation procedures: Application to extreme wind data [C]. In: Galambos, J. (ed.), Extreme value theory and applications. Printed in the Netherlands: Kluwer Academic Publishers., pp 139–158.

Gusella, V. 1991. Estimation of extreme winds from short-term records [J]. Journal of Structural Engineering, **117**: 375–390.

Hannah, P., Palutikof, J.P. and Quine, C.P. 1995. Predicting windspeeds for forest areas in complex terrain [C]. In: Coutts, M. P. and

Grace, J. (eds.), Wind and trees. Cambridge: Cambridge University Press, pp 113–132.

Ishizaki, K. and Ota, M. 1987. Wind profiles above a forest canopy [J]. Research Bulletin of the Hokkaido University Forest, **44**: 416–475.

Kaimal, J.C. and Finnigan, J.J. 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement [M]. New York - USA: Oxford University Press, 302 pp.

Kimmins, J.P. 1987. Forest Ecology [M]. New York, Macmillan, London, Collier Macmillan, 531 pp.

Kondo, J. and Akashi, S. 1976. Numerical studies on the two-dimensional flow in horizontal homogeneous canopy layers [J]. Boundary-Layer Meteorology, **10**: 255–272.

Kotoda, K. and Hayashi, Y. 1980. On the wind profile above plant canopies and its aerodynamic properties [J]. Journal of Agricultural Meteorology, Japan, **35**: 221–228. (in Japanese with English abstract)

Kuraji, K., Tanaka, N., Shiraki, K., Karakama, I. and Ohta, T. 1997. Effects of windspeed on stem-flow volume in a mature *Cryptomeria japonica* and *Chamaecyparis obtusa* stand [J]. Journal of Forest Research, Japan Forestry Society, **79**: 215–221. (in Japanese with English abstract)

Landsberg, J.J. and James, G.B. 1971. Wind profiles in plant canopies: studies on an analytical model. Journal of Applied Ecology, **8**: 729–741.

Lemone, M.A., Zhou, M. Y., Money, C.H., Lenschow, D.H., Mille, L. J. and Grossman, R.L. 1998. An observational study of wind profiles in the barochinic convective mixed layer [J]. Boundary-Layer Meteorology, **90**: 47–82.

Liu, J.M. and Kotoda, K. 1996. Evaluation of surface-layer wind profiles with HEIFE observations [J]. Boundary-Layer Meteorology, **83**: 27–41.

Lyles, L. and Allison, B.E. 1979. Wind profile parameters and turbulence intensity over several roughness element geometries [J]. Transactions of the ASAE, **22**: 334–343.

Maki, T. 1999. Wind and nature [M]. Tokyo: Kaihutsushia Press, 239 pp. (In Japanese)

Miller, J.F. 1982. Precipitation evaluation in hydrology [C]. In: Plate, E. (ed.), Engineering meteorology Studies in wind engineering and industrial aerodynamics 1. Amsterdam, Oxford, New York: Elsevier, Scientific Publishing Company, , pp 371–424.

Milne, R. 1992. Extreme wind speeds over a Sitka spruce plantation in Scotland. Agricultural and Forest Meteorology, **61**: 39–53.

Munn, R.E. 1966. Descriptive Micrometeorology [M]. Academic press, New York, San Fransisco, London, 245 pp.

Murai, H., Ishikawa, M., Endo, J. and Tadaki, R. 1992. The Coastal Forests in Japan [M]. Tokyo: Soft Science, INC.,513 pp. (in Japanese)

Oliver, H.R. 1971. Wind profiles in and above a forest canopy [J]. Quarterly Journal Royal Meteorological Society, **97**: 548–553.

Oliver, H.R. and Mayhead, G.J. 1974. Wind measurements in a pine forest during a destructive gale [J]. Forestry, **47**: 185–195.

Oliver, H.R. 1975. Wind speeds within the trunk space of a pine forest [J]. Quarterly Journal Royal Meteorological Society, **101**: 167–168.

Peltola, H. 1996b. Model computations on wind flow and turning movement by wind for Scots pines along the margins of clear-cut areas [J]. Forest Ecology and Management, **83**: 203–215.

Peltola, H., Kellomaki, S., Kolstrom, T., Lassig, R., Moor, J., Quine, C. and Ruel, J.C. 2000. Wind and other abiotic risks to forests [J]. Forest Ecology and Management, **135**: 1–2.

Plate, E.J. 1971. The aerodynamics of shelterbelts [J]. Agricultural Meteorology, **8**: 203–222.

Quine, C.P. 2000. Estimation of mean wind climate and probability of strong winds for wind risk assessment [J]. Forestry, **73**: 247–258.

Raynor, G. 1971. Wind and temperature structure in a coniferous forest and a contiguous field [J]. Forest Science, **17**: 351–363.

Reifsnyder, W.E. 1955. Wind profiles in a small isolated forest stand [J]. Forest Science, **1**: 189–297.

Simiu, E. and Filliben, J.J. 1980. Weibull distributions and extreme wind speeds [J]. Journal of Structural Division, **106**: 2365–2374.

Simiu, E. and Filliben, J.J. 1982. Short term records and extreme wind speeds [J]. Journal of Structural Division, **108**: 2571–2577.

Simiu, E., Hendrickson, E.M., Nolan, W.A. and Olkin, I. 1985. Multivariate distributions of directional wind speeds [J]. Journal of Structural Division, **111**: 939–943.

Simiu, E. and Heckert, N.A. 1996. Extreme wind distribution tails: a "peaks over threshold" approach [J]. Journal of Structural Engineering, **122**: 539–547.

Taketa, K. 1964. Turbulence in plant canopies [J]. Journal of Agricultural Meteorology, Japan, **20**: 1–5. (in Japanese with English abstract)

Taketa, K. 1965. Turbulence in plant canopies (2) [J]. Journal of Agricultural Meteorology, Japan, **21**: 11–14. (in Japanese with English abstract)

Telewski, F.W. 1995. Wind-induced physiological and developmental responses in trees [C]. In: Coutts, M. P. and Grace, J. (eds.), Wind and trees. Cambridge: Cambridge University Press, pp 237–263.

Thom, A.S. 1971. Momentum absorption by vegetation [J]. Quarterly Journal Royal Meteorological Society, **97**: 414–428.

Thom, A.S. 1972. Momentum, mass and heat exchange of vegetation [J]. Quarterly Journal Royal Meteorological Society, **98**: 124–134.

Xie, Dingyu. 1987. Fluid mechanics [M]. Press of Nankai University, Tianjin, 233 pp. (in Chinese)

Zhu, J.J., Matsuzaki, T., Sakioka, K. and Yamamoto, M. 1998. Windspeed in a coastal forest belt of Japanese black pine (*Pinus thunbergii* Parl.): Vertical wind profile [J]. Transactions of the Japanese Forestry Society, **109**: 455–458.

Zhu, J.J., Matsuzaki, T. and Sakioka, K. 2000. Windspeeds within a single crown of Japanese black pine (*Pinus thunbergii* Parl.) [J]. Forest Ecology and Management, **135**: 19–31.

Zhu, J.J., Matsuzaki, T. and Gonda, Y. 2001a. Wind profiles in a coastal forest of Japanese black pine (*Pinus thunbergii* Parl.) with different thinning intensities [J]. Journal of Forest Research, the Japanese Forestry Society, **6**: 287–296.

Zhu, J.J., Matsuzaki, T. and Gonda, Y. 2001b. Extreme wind over a pine coastal forest plantation at Aoyama of Niigata in Japan [J]. Journal of the Japan Society of Erosion Control Engineering, **54**: 12–20.

Zhu, J.J., Matsuzaki, T. and Jiang, F.Q. 2004. Wind on Tree Windbreaks [M]. China Forestry Publishing House, Beijing, 235 pp.